Negative ions for heavy ion fusion and semiconductor manufacturing applications

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Radio frequency driven multicusp source was set up to run chlorine plasma and the source performance was compared between positive and negative chlorine ion production. A maximum Cl^- current density of 45 mA/cm^2 was achieved at 2.2 kW of rf power with electron to negative ion ratio of 7 and positive to negative ion ratio of 1.3. 99.8% of the total negative chlorine beam was atomic Cl^-. To produce negative boron ions for semiconductor manufacturing applications, a noncesiated, sputtering-type surface production ion source was constructed. An external rf antenna geometry and large LaB_6 converter were implemented in the source design. Maximum B_2^- ion current density of 1 mA/cm^2 was achieved at 800 W of rf power and −600 V converter voltage. Total B_2^- ion current was 1.8 mA. [DOI: 10.1063/1.1699455]

I. INTRODUCTION

The applicability of heavy negative ions as the drivers of inertial confinement fusion and in ion implantation applications has been studied in the Plasma and Ion Source Technology Group at the Lawrence Berkeley National Laboratory. In fusion applications, negative ions provide a way of producing a totally space charge neutralized beam of stripped, neutral particles, thus avoiding beam-plasma and space charge instabilities. Halogens are the most promising candidate for heavy negative ion driver beams. In ion beam implantation the charging up of the material can be avoided by using negative ions instead of positive ones.

II. NEGATIVE Cl^- IONS FOR HEAVY ION FUSION APPLICATIONS

A. Motivation for the experiment

In heavy ion fusion applications, negative ions provide a way of producing a totally space-charge neutralized beam of neutral particles at the end of the accelerator and expel electrons while inside the accelerator.

The best candidates for heavy negative ion driver beams for inertial confinement fusion can be found among the halogens in the periodic table of elements.[1] In particular bromine (mass number 81, electron affinity 3.36 eV) and iodine (mass number 127, electron affinity 3.06 eV) would be suitable for heavy ion fusion due to their large mass and high electron affinity. These elements would have to be heated to a vapor and the ion source has to operate at elevated temperatures to prevent the condensation of the vapor on cold surfaces. For initial estimates of achievable negative ion current densities from halogens chlorine was selected for this experiment. It has similar electron affinity (3.61 eV) to bromine and iodine, and high enough mass number (35). It is also commercially available in gaseous form, and thus existing volume type ion source technology could be utilized in this experiment.

B. Experimental setup

The experimental system that was used in the negative chlorine experiment is presented in Fig. 1. The ion source was a 10 cm diam, 15 cm long multicusp source driven by a 13.56 MHz rf power supply and accompanying matching network. The rf antenna used in the experiment was a 1.5 turn titanium conductor tube running inside a larger quartz tube. The multicusp magnetic field was created by 20 rows of SmCo magnets surrounding the plasma chamber. A dipole magnetic field with 135 G peak field and 2.4 cm full width half maximum was created inside the plasma chamber to divide the ion source volume into discharge and extraction regions to optimize the formation of Cl^- ions through dissociative attachment process. The ion extraction was a two-electrode system with a movable Faraday cup for ion current measurement. A dipole magnetic field acting as an electron filter was built into the puller electrode to remove the electrons from the extracted negative beam. The electron beam was dumped into a water cooled Mo target. An electrostatic Einzel lens was used to match the extracted ion beam into a magnetic mass spectrometer, which was used as a mass analyzer to separate the different ion species in the ion beam. A pepper pot emittance measurement device was installed in the place of the Faraday cup for beam emittance measurements.

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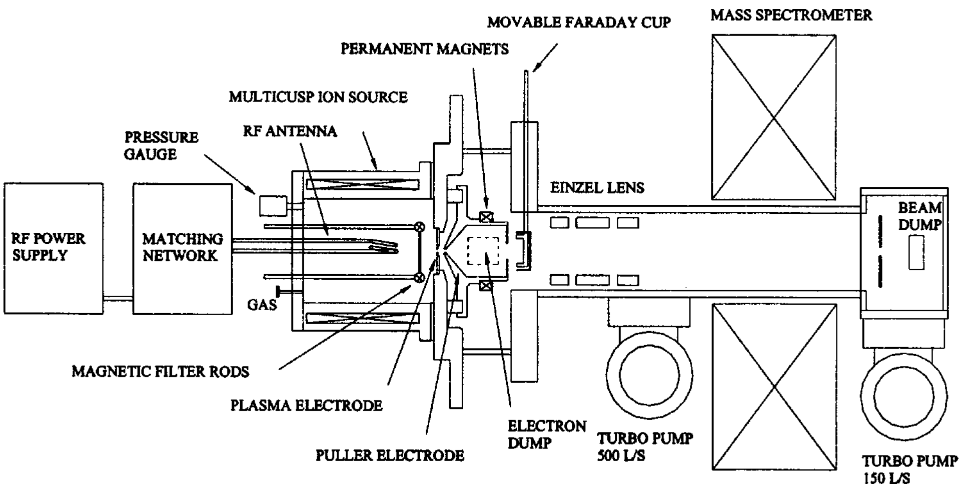

FIG. 1. Schematic of the experimental setup used in the negative chlorine experiment.

C. Experimental results

The ion source performance was characterized for both positive and negative chlorine ion beams.[2,3] In Fig. 2, the measured positive and negative chlorine ion spectrums are presented. About 80% of the positive chlorine ions and 99.8% of the negative chlorine ions were atomic Cl^+ and Cl^-, respectively. Figure 3 shows the measured Cl^- current density as a function of rf power and ion source pressure. The current density increased linearly as a function of rf power at source pressures above 20 mTorr. The maximum Cl^- current density achieved in the measurements was 45 mA/cm^2 at 2.2 kW of rf power, which was the limit of the rf power supply, and at 32 mTorr source pressure. All the measurements were done using a 2 mm diam extraction aperture. The ratio of measured electron to Cl^- currents was 7, indicating that up to 99% of the negative charge in the extraction region of the chlorine plasma was Cl^- ions. The ratio of the measured Cl^+ and Cl^- currents was 1.3. The ion beam emittance was measured using a pepper pot emittance measurement device. Ion transverse temperatures in parallel and transverse directions to the electron filter magnetic field for the negative chlorine were 0.3 and 0.5 eV, respectively. For positive chlorine the temperatures were 0.2 and 0.5 eV. Figure 4 shows the measured geometric emittances for Cl^+ and Cl^- ion beams at 1.5 kW of rf power, 35 mTorr source pressure, 2 mm extraction aperture, and ion currents of $I_{Cl+}=0.83$ mA and $I_{Cl-}=0.65$ mA. For the positive chlorine beam the emittance $\varepsilon=134\ \pi$ mm mrad and the normalized emittance $\varepsilon_n=0.12\ \pi$ mm mrad. For negative chlorine beam $\varepsilon=157\ \pi$ mm mrad and $\varepsilon_n=0.14\ \pi$ mm mrad. The current and emittance measurements indicate that negative halogen ions are good candidates for heavy ion fusion driver beams, as the source performance was very similar for both positive and negative chlorine ions. The fact that the Cl^- current went up linearly as a function of rf power would indicate that even higher Cl^- currents should be achievable by using higher rf power levels. The experiment described here was limited to 2.2 kW of rf power and cw operation.

III. A SPUTTERING TYPE SURFACE IONIZATION SOURCE WITH EXTERNAL rf ANTENNA AND NONCESIATED OPERATION FOR PRODUCTION OF B_2^- IONS

A. Motivation for the experiment

When negative ions are used in ion implantation, the emitted charge of the secondary electrons is balanced by the negative charge of the incoming ions. The surface will acquire a positive voltage of only a few volts. This is why methods of negative boron ion production have been researched by several groups.[4,5]

The ion sources reported in Refs. 4 and 5 are sputtering type surface production ion sources capable of producing 1–2 mA of B_2^- ions. Background Ar plasma is created using an internal rf antenna and the negative ionization efficiency is enhanced by feeding cesium into the source chamber. This

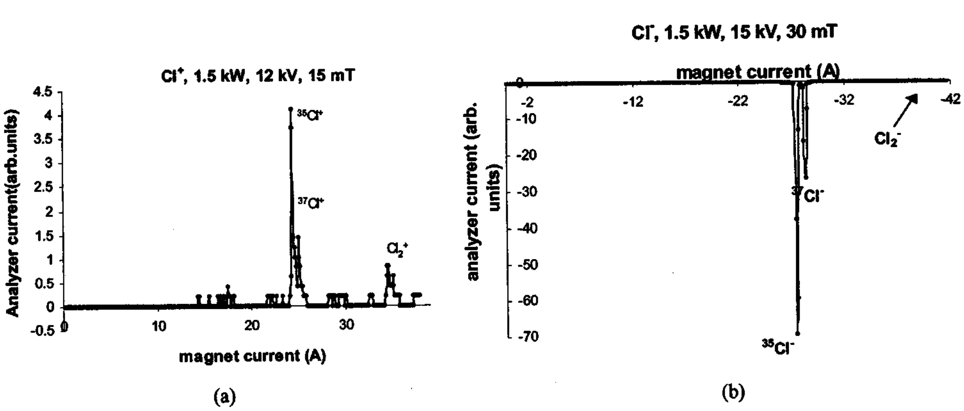

FIG. 2. (a) Positive and (b) negative chlorine ion mass spectrum at 1.5 kW rf power.

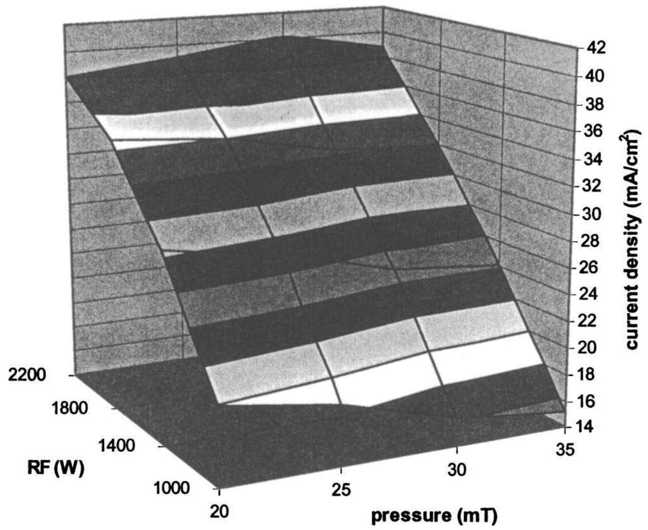

FIG. 3. The extracted Cl^- current density from a 2 mm diam extraction aperture as a function of rf power and ion source pressure.

type of source can suffer from lifetime issues due to the placement of the rf antenna inside the plasma and the use of cesium, which coats insulator surfaces in the accelerator column and can cause voltage breakdowns. To overcome these problems, a sputtering-type surface production ion source with an external rf antenna and non-cesiated operation was designed and constructed at the Plasma and Ion Source Technology Group at the LBNL.

B. Experimental setup

The ion source constructed for the experiment is shown in Fig. 5. The source body is a 80 mm long, 75 mm inner diameter quartz tube around which the antenna loops are wrapped. The quartz tube sites in the o-ring grooves on both the front and back plates. The back plate is suspended from the front plate by six insulator rods, which also take the mechanical load instead of the quartz cylinder. A 50 mm diam LaB_6 converter is clamped to the back plate by a stainless steel collar, which is shielded from the plasma by an aluminum oxide ring. The back plate of the ion source and the LaB_6 converter are biased to -600 V negative bias with

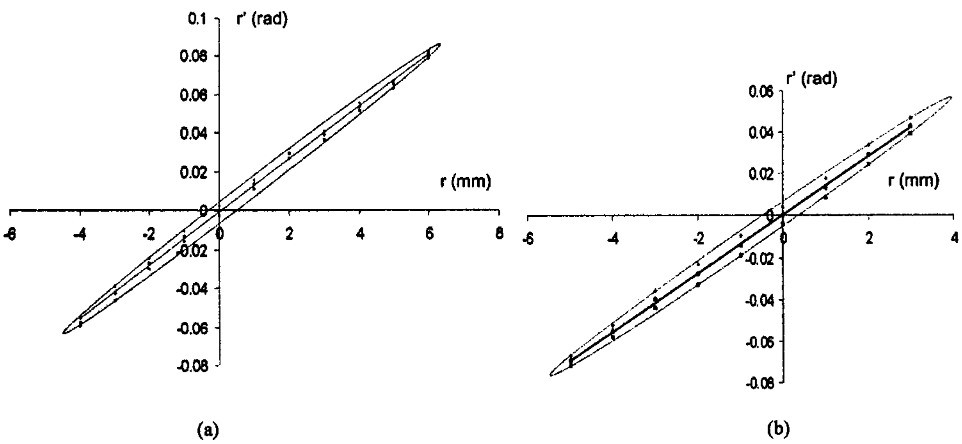

FIG. 4. The measured geometric emittances for Cl^+ and Cl^- ion beams at 1.5 kW of rf power, 35 mTorr source pressure, 2 mm extraction aperture, and $I_{Cl+}=0.83$ mA and $I_{Cl-}=0.65$ mA. For Cl^+ the normalized emittance $\varepsilon_n=0.12\ \pi$ mm mrad and for Cl^- $\varepsilon_n=0.14\ \pi$ mm mrad.

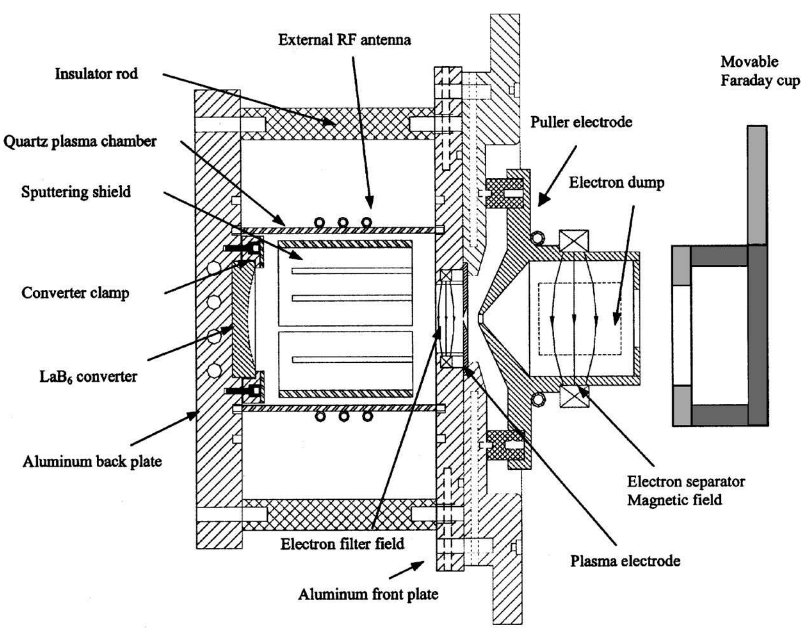

FIG. 5. The LaB_6 sputtering ion source with an external rf antenna.

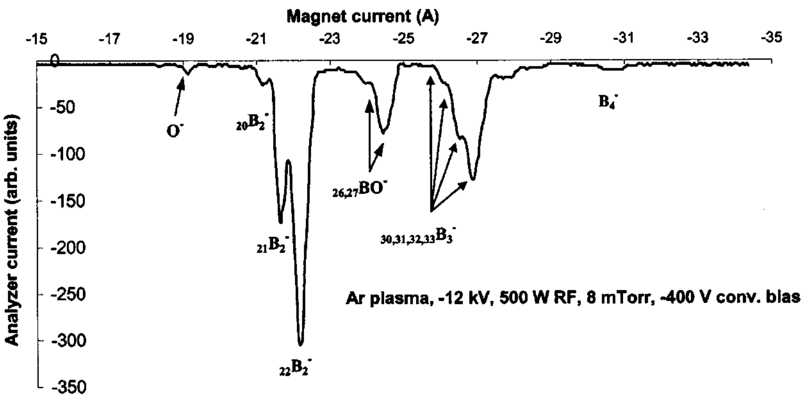

FIG. 6. Negative ion spectrum from the external rf antenna LaB_6 converter source.

respect to the front plate. This accelerates positive Ar^+ ions from the background plasma towards the converter, which results in sputtering of lanthanum and boron atoms. Some of these sputtered atoms are turned into negative ions as they pass the low work function (2.36 eV) LaB_6 surface.

A 70 mm diam quartz cylinder with ten slots was installed inside the plasma chamber. As material is sputtered from the converter, the walls of the plasma chamber are covered by lanthanum and boron. Since lanthanum is a metal, the sputtered layer will be conducting. This would create a Faraday shield between the rf antenna and the plasma volume in which the rf field will induce circular currents that will lead into the loss of rf power into the sputtered layer instead of the plasma. By installing a slotted sputtering shield with one of the slots going all the way through the length of the tube the formation of a closed conducting layer can be prevented and the rf field will not be cancelled out. The external antenna geometry combined with the sputtering shield will enable a high power, long lifetime cw operation of the ion source as the antenna is not exposed to the destructive environment of plasma.

A pair of filter magnet rods were installed inside the front plate. The magnetic field turns away the secondary electrons emitted from the converter surface. The field also lowers the plasma density in front of the extraction aperture and thus lowers the extracted volume electron current.

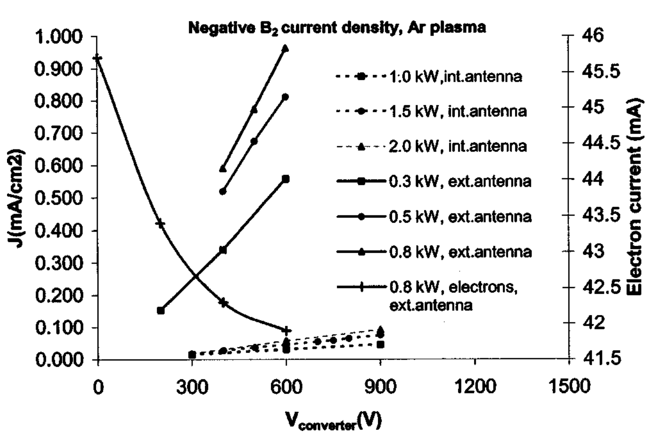

FIG. 7. B_2^- current density as a function of the rf power measured with the external rf antenna sputtering ion source and with a large multicusp sputtering source with an internal rf antenna (see Ref. 2).

The rf antenna coil is a simple 3 mm diam copper tube with cooling water running inside. 13.56 MHz rf amplifier with an inductive matching network was used to drive the plasma. The test stand in which the sputtering source was operated was the same one as described in Sec. II B.

C. Experimental results

The ion source chamber length was selected so that the distance from the converter surface to the extraction aperture was 75 mm, which matched the radius of curvature of the converter. The sputtering shield was kept in the source for all measurements. Figure 6 shows a negative ion spectrum from argon plasma at 300 W rf power, 8 mTorr source pressure, -8 kV extraction voltage, and -400 V converter bias.

The beam fractions remained the same at different rf power levels and converter voltages. About 62% of the beam was determined to be B_2^-, 27% was B_3^-, 10% was BO^-, and 1% O^-. Figure 7 shows the measured B_2^- ion current density measured with the new sputtering ion source at 300, 500, and 800 W rf power at 10 mTorr source pressure. B_2^- ion current densities measured with a large multicusp sputtering source with an internal antenna, 20 mm diam LaB_6 converter and noncesiated operation are also plotted in Fig. 7.

The maximum achieved B_2^- current density with the new sputtering ion source was about 1 mA/cm^2 at 800 W of rf power, 10 mTorr source pressure, and -600 V converter bias. The beam spot diameter on the plasma electrode was about 15 mm. If the current density in the beam spot is assumed to be nearly uniform the corresponding total B_2^- current at the plasma electrode plane is 1.8 mA.

ACKNOWLEDGMENTS

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